Chemical Engineering Science 116 (2014) 486–496

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Vortical structures swept by a bubble swarm in turbulent boundary layers

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HIGHLIGHTS

- Two-color sheet illumination allows wall turbulence to be visualized quantitatively.
- Transient influence of a bubble swarm on the turbulence is graphically elucidated.
- Vortical structures of the turbulence are swept from the wall by the bubble swarm.
- Swept structures survive on the backside of the swarm.

ARTICLE INFO

Article history:
Received 25 January 2014
Received in revised form
11 April 2014
Accepted 10 May 2014
Available online 22 May 2014

Keywords:
Bubble
Multiphase flow
Turbulence
Boundary layer
Visualization

ABSTRACT

Bubbles injected into a wall turbulent boundary layer can modify heat, mass, and momentum transfers of the wall. One factor responsible for the phenomenon is alternation of the vortical flow structures near the wall. To demonstrate this graphically, we directly visualized the interaction between the vortical flow structures and a bubble swarm composed of bubbles with various sizes, by means of two-color laser-sheet illumination of the wall turbulence with a dilute suspension of flakes. Image processing realized quantitative characterization of interaction events in the buffer and logarithmic layers, referring to multiple measured quantities such as the relative advection velocity between bubbles and turbulence, spacing of vortices both in streamwise and spanwise directions, persisting lengths of vortices in both directions, and statistical inclination angles of the streamwise vortices. A particular finding from the present visualization is that the streamwise vortices in the buffer layer were swept by the bubble swarm but brought to the backside of the swarm to survive until the swarm passed by.

1. Introduction

Bubbly two-phase flows still pose various questions despite a long history of study. Conventional theoretical modeling has limitations in precisely reproducing the complex effects of deformation, coalescence and fragmentation of bubbles on the behavior of two-phase flow. This is the so-called multi-scale problem of bubbly flow (e.g., Sugiyama et al., 2001), which ranges from the thickness of a gas–liquid interface, via the bubble size, to the length scale of a bulk system. This nature of bubbly flow accompanied by a broad spectrum in the flow structure always brings us difficulties in prediction and control, especially for bubbly two-phase turbulent boundary layer. In this context, our research has focused on finding local instantaneous phenomena in the wall boundary layer associated with bubbles, expecting that the solution will lead to breakthrough technologies in chemical, biological, thermal, and fluid engineering.

Most engineering processes utilizing bubbly flows have a solid wall as a boundary of the system. In the case of a vertical system, intensive works have been reported for vertical bubbly pipe flows because of industrial demands for boilers and heat exchangers (Hibiki and Ishii, 2002). Two-phase flow patterns in pipes affect the heat transfer and pressure loss characteristics (Deckwer, 1980; Heijnen and Riet, 1984; Joshi et al., 2002). The same flows in very small geometry have totally different characteristics, which has opened a new field of research on microscopic thermo-chemical devices (Qu and Mudawar, 2003; Kandlikar, 2004). A significant promotion of heat transfer by the injection of microbubbles about the thermal boundary layer was reported by Kitagawa and Murai (2013). Their experiment showed that bubbles work as a thermal transporter in turbulence while the bubbles themselves are thermal insulators in the region without turbulence.

Horizontal configurations of bubbly flow have received less attention than vertical systems in engineering fields since it is

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http://dx.doi.org/10.1016/j.ces.2014.05.026

unsuitable for stable heat and mass transfers. In a horizontal main stream, buoyancy acts on dispersed bubbles perpendicularly to the stream so that the flow field is multi-dimensionalized irresistibly. In a boundary layer formed beneath a horizontal flat wall, bubbles congregate near the wall to persistently affect the inner-layer structure of the wall turbulence. Synchronically, turbulent shear stress and resultant eddies affect the spatial and size distributions of bubbles. Bubbly flow structure in the equilibrium states of such mutual interaction can hardly be predicted theoretically if we are unaware of what happens to the local two-phase turbulence. Accordingly, a well-schemed experimentation is desired to achieve a graphical understanding of bubble–vortex two-way interaction, which will contribute to all applications of heat, mass and momentum transfer using bubbles in horizontal flow configurations.

Our objective in the present study also has strong relevance to the frictional drag reduction by injection of bubbles, i.e. decrease in turbulent momentum transfer of a solid wall. Since the paper of McCormick and Bhattacharyya (1973) for ship drag reduction, horizontal bubbly flow close to a wall has been investigated by many institutes over 40 years and it concluded that the use of such flow is feasibly practical although the underlying physics are still unsolved comprehensively (Ceccio, 2010). Drag reduction using bubbles is classified roughly into two types by bubble size. In the first case, drag reduction is achieved with bubbles that are sufficiently smaller than the thickness of the boundary layer (Kato et al., 1999), which is often called microbubble drag reduction. In the second case, air films are formed to occupy the wall surface and thus separate turbulent flow from the wall (Latorre, 1997; Fukuda et al., 2000). These two methods have different mechanisms of drag reduction. Coherent structures of quasi-streamwise vortices, which are generated in the wall boundary layers, are the targets of fluid dynamic curiosity because they have a strong relation with the wall frictional drag (Robinson, 1991; Kravchenko et al., 1993). Iwasaki et al. (2001) simulated numerically such streamwise vortices are affected by the presence of deformable bubbles, and Lu et al. (2005) found with their simulation that soft deformation of bubbles leads to a significant drag reduction as the streamwise vortices around them are suppressed. Additionally, alternation of streamwise vortices due to mixing of microbubbles was ascertained by the experiments in the last decade (Hassan et al., 2005; Zhen and Hassan, 2006). Oishi et al. (2007) found that microbubbles of micron size shorten the streamwise vortices and incline them in the spanwise direction even though their volume fraction is less than 1%. Between the two approaches of microbubbles and air films, the role of intermediate-sized bubbles has not yet been clarified. The intermediate-sized bubbles, named here, range from 1 mm to 100 mm in characteristic length scale, which is comparable with or larger than typical thickness of turbulent boundary layer in engineering such as for ships. The number of intermediate-sized bubbles increases naturally during the migration of various sized bubbles downstream owing to coalescence of small bubbles and fragmentation of large bubbles in turbulent shear flow. Thus, from both aspects of engineering and science, we are facing a strong need for fundamental knowledge on turbulence–bubble interaction in the whole range of bubble sizes.

The authors' group has constructed an experimental facility to investigate the local and transient reactions of a boundary layer given an injection of bubbles. One of the representative results obtained by the group is that relatively small bubbles produce a negative turbulent shear stress component that correlates to fluctuation of the local void fraction (Murai et al., 2006). Another finding, for relatively large bubbles, is that an air film works properly when the bubbles are longer than five times the boundary layer thickness in the streamwise direction (Murai et al., 2007). In other words, shorter bubbles behave as neutral additives in drag reduction. Further interesting results were obtained by Oishi et al. (2009), who showed the waveform of the local skin friction when the void fraction has a naturally provided fluctuation and found that the average drag reduction is promoted by amplifying the fluctuation in the local void fraction. This phenomenon is hypothetically explained by the non-linear relationship and the time lag between drag reduction ratio and the local void fraction. On one hand, we already know that there is a contribution of a single large bubble passing the wall intermittently to the drag reduction. Oishi and Murai (2014) measured the turbulent shear stress field modified by such a single bubble passage in the vicinity of wall. On the other hand, intermittent passage of bubbles' ensemble would produce the similar effect. To prove the scenario, we introduced artificial waves in the void fraction to determine the drag reduction characteristics, and succeeded in promoting drag reduction through the repetitive injection of bubble swarms composed of bubbles of various sizes (Park et al., 2009). Measurements of velocity profiles and variations of local wall shear stress indicated that controllability of drag reduction was improved with this technique, and also the positive contribution of the intermediate-sized bubbles to the time-averaged drag reduction was confirmed for the first time. This result means that the passing bubble swarm modifies vortical structures more effectively, which are the source of turbulent momentum transfer, i.e. turbulent shear stress. Following to the methodology of artificial pulsation in void fraction, we investigate how turbulent flow structures (vortical structures) are altered by a bubble swarm using an originally developed visualization technique so that enhancement mechanism of the drag reduction by means of repetitive bubble injections is understood.

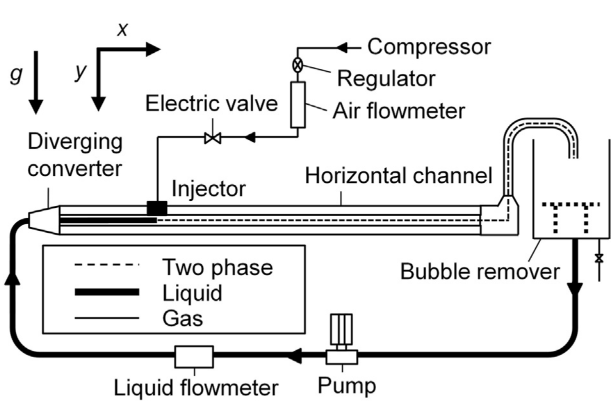

Fig. 1. Schematic diagram of the experimental facility.

2. Experimental setup

A schematic diagram of the experimental facility is shown in Fig. 1. The test section is a horizontal rectangular channel made of transparent acrylic resin. The test section is 40 mm in height ($H=2h$), 160 mm in width (W) and 6000 mm in length. Test fluid is 10 cSt silicone oil at 28 °C; density (ρ) of the oil is 932 kg/m^3, kinematic viscosity (ν) is 7.7×10^{-6} m^2/s, and surface tension (σ) is 19.9×10^{-3} N/m. Using the oil avoids effects of contamination on bubble interfaces and allows large deformation of the bubbles even for turbulent flows with relatively low Reynolds numbers because the surface tension of the oil is lower than that of water. The silicone oil circulates in the channel, and bubbles are mixed through honeycombed holes of a bubble injector mounted on the upper wall of the channel at $x/H=43.75$ from the channel inlet, where the boundary layer is in a turbulent condition. We define x,